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Subject: **Profiled Roller Stress/Fatigue Life Analysis Methodology and Establishment of an Appropriate Stress/Life Exponent** - Results Summary

Reference: OAI Project NAG3-1938-JPA

This letter report contains the pertinent results of work conducted under the referenced OAI project.

OBJECTIVE OF WORK

The objective of this work was to determine the three dimensional volumetric stress field, surface pressure distribution and actual contact area between a 0.50" square roller with different crown profiles and a flat raceway surface using Finite Element Analysis. The 3-dimensional stress field data was used in conjunction with several bearing fatigue life theories to extract appropriate values for stress-life exponents. Also, results of the FEA runs were used to evaluate the laminated roller model presently used for stress and life prediction.

APPROACH

Our approach was to develop a 3-Dimensional finite element model geometry of a 0.5" x 0.5" profiled roller contacting a flat raceway and utilize the model to determine the actual surface pressure, contact area and volumetric stress fields developed within the raceway material for four profile shapes and at three Hertz stress levels. The four standard profiles studied were as follows:

* Flat or Straight Roller
* Roller With Flat Length + End Taper
* Fully Crowned Roller
* Aerospace Crown (Flat Length + Crown Radius)

Each roller profile model was run at nominal Hertz contact stress levels of 350,000 psi, 275,000 psi and 200,000 psi maximum stress. Subsequently, calculated Von Mises, In-Plane Shear, Orthogonal Shear, element volumes and depths were extracted from the FEA runs to form a stress data base for determination of stress-life exponents according to the various life theories of current interest. The FEA model computed maximum interface contact stress was also noted for comparison with those derived using the "laminated" roller model as applied to the four crown profiles being studied.

RESULTS

The results of these studies are presented in the attached tables. Tables I to III summarize pertinent stress, depth and model data for each of the values of nominal Hertz stress studied. Hertz line contact stress theory was used to calculate an applied load that corresponds to the specific nominal value of Hertz stress. For example, a 3149# load would give 350,000 psi Max. Hertz stress on the 0.5" roller. Table I shows that the same load would result in different Hertz stress levels depending on the roller profile. The FEA model Center Surface Hertz stress listed in Table I shows that the Max. Hertz stress varies from 411,000 psi for the fully crowned roller to a minimum of 361,000 psi for the roller with end-taper. This trend also appears in Tables II and III.

STRESS-LIFE EXPONENT

The basic data in Tables I to III was combined with the corresponding 3-dimensional volumetric stress field data bases to estimate stress/life exponents that are derived from the three fatigue life models of interest. Tables IV-VI show the corresponding "Relative Life" and back calculated stress/life exponents for the Zaretsky-Weibull, Lundberg-Palmgren and Ioannides-Harris life theories. The method used is discussed in a similar study of a ball contact by Zaretsky, Poplawski and Peters (1996). These calculations were performed by normalizing the study to the 350,000 psi maximum Hertz stress values.

Table IV shows back calculated Stress/Life exponents if one were to choose the Von-Mises stress as the stress of comparison. The Zaretsky-Weibull (ZW) model estimates stress -life exponents in the range of 8.6 to 14.3 depending on the profile and stress level selected. These values are very reasonable. The corresponding values of 21.7 to 31.2 for the Flat roller imply a more sensitive behavior. This is due to the edge stress developed in this roller. The classical Lundberg-Palmgren (LP) theory estimates exponents in the range of 8.7 to 14.7 for the Aerospace, Full Crown and End Taper profile. These compare well with the WZ theory. For the flat roller the exponents increase to 24.9 to 38.6. Once gain, this sensitivity increase is due to the edge stress concentration.

The Ioannedis-Harris (IH) theory requires one to select a value for the Endurance Limiting Stress for infinite life. IH publications regarding their theory have shown different values for this stress for the same material. Therefore, we exercised this theory for several limiting stresses that cover the range of values seen in their papers. For high values of limiting stress, large exponents in the range of 24 to 52 are derived. These are about 3 times those derived from the WZ and LP theories. For low values of limiting stress, the exponents begin to approach those of LP and WZ. An independent experimental test would have to be designed to determine the physical property of Limiting Stress as opposed to using a value that allows theory- bearing test data match.

Table V presents relative life and extracted exponents using the Maximum In-Plane Shear stress typically referred to as Tau 45. The stress-life exponents (excluding the flat roller) are reasonable using the ZW and LP theories. These values increase for the flat roller as previously discussed. Once again, the IH theory gives unreasonable high values that decrease as the selected limiting stress is reduced.

Table VI repeats the study using the Orthogonal Shear stress. The resulting exponent magnitudes and trends are similar to the previous results.

LAMINATED ROLLER Model

A "stand alone" computer program called **CROWN** was developed using the approach of Radzimovsky (1953) to determine the non-uniform stress pattern across a profiled misaligned roller. The program analyzes a single roller contact of a crowned roller under Load and Misalignment by "slicing" the roller into thin disks or lamina. An iterative solution is required to determine the non-uniform load pattern developed across the roller interface. Upon reaching equilibrium, the lamina contact stress is calculated using Hertz 2-D line contact stress theory. That stress is assumed to be uniform across the width of 1 lamina. As previously mentioned, the "lamina" approach has been used from the early programs of Jones (1960) to more recent programs such as SHABERTH (1981). This method has provided a design tool for analyzing crowned rollers for many years.

The laminated roller model does not predict stress concentration at the edge of the roller if it contacts the race. Therefore, designers attempt to add enough crown to avoid edge contact or to keep the edge stress estimated with the model to a very low value. Also, since this model is numerical in nature, the number of lamina placed across the roller should govern the accuracy of the solution. More accuracy requires increasing the number of lamina. However, this also adds computational time. Many computer codes set the number of slices at 20. Some analysts have complained that more slices are needed to better represent the roller. Arguments have developed with regard to this issue. Also, the laminated roller models inherent in these codes are used to model fully crowned rollers. The calculation of contact stress in a fully crowned roller requires the use of 3-D Hertzian elliptical contact stress theory. Stresses calculated with 2-D theory at the interface of a slice in a fully crowned roller will underestimate the stress. This may have a significant effect on the life estimate since stress and life are inversely proportional to a 9 to 12 power.

CROWN Program Results

The stress distribution for each of the 4 crown profiles on the 0.5" square roller were analyzed at nominal contact stress levels of 275 ksi, 300 ksi and 350 ksi using the CROWN program. This was done while the number of "lamina" were varied from 10 to 80. The results showed that the calculated stress pattern across the roller did not vary as a function of the number of lamina used. However, The contact life would be different since lamina width does change.

The L10 Fatigue Life of the contact was determined using the SHABERTH and our BRG programs. A "dummy" radial bearing having 4 rollers was analyzed by applying a radial load to the bearing equivalent to the roller load used in the previous analysis. In such a bearing, a roller resides at 0, 90, 180 and 270 degrees location. Thus, under radial load, only the roller at 180 degrees or Bottom Dead Center is loaded to a value equal to the applied load. An inner ring rotational speed was assumed at 100.

Table VII compares L10 life estimates for each roller model with different number of lamina. These results indicate that a lamina width of 10% or less of the roller length was required for accurate life estimation.

L10 Fatigue Life estimates via a laminated roller models in our BRG program were compared to those of SHABERTH. Table VIII shows that the stress level and L10 life estimates that were predicted using each code agreed very well.

Finally, the adequacy of the laminated roller model to represent a "fully crowned" roller was investigated by comparing the estimated Maximum Hertz stress from the CROWN program to Hertz 3-D elliptical contact theoretical calculations. Table IX compares the Hertz stresses from a 20 and 40 lamina model to theoretical predictions. Notice that at the 200ksi and 275ksi nominal levels, the laminated roller model is underestimating the stress in the fully crowned roller by 2.5% to 3.5%. This corresponds to underestimating life by 24 to 37% using a stress-life exponent of 9. At the 350ksi nominal stress level, the ellipse semi-length is beyond the end of the roller giving an inaccurate stress estimate for this roller.

CONCLUSIONS

The results of this study have led us to conclude that:

1. The Zaretsky-Weibull and Lundberg-Palmgren fatigue life theories yield reasonable and believable stress life exponents when applied to line contact bearings. This was true for the decisive stress choices of the Von Mises, Tau 45, and Orthogonal Shear stress. The same would be true for the Octahedral shear stress since it related to the Von-Misis by a constant.

2. The Ionnides-Harris theory would significantly over estimate life due to the high values derived for the stress-life exponents. This was true for all of the decisive stresses selected.

3. The across roller stress profile, determined using the laminated roller model, was insensitive to the number of lamina used.

4. A lamina width equal to 10% or less of the roller width was required for accurate roller life prediction.

5. A lamina model representation of fully crowned rollers resulted in underestimating stress by 2.5% to 3.5% with a corresponding underestimated life of 24% to 34% at the stress levels studied.

A much more detailed report is being prepared and will contain details of the FEA model and supportive stress plots, charts and graphs.

Very truly yours;

J.V. Poplawski

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TABLE I. STRESS DATA SUMMARY FOR 350 KSI NOMINAL STRESS

3149 # Load
350,000 psi nominal

Crown	AeroSpace	Full	Flat	End-Taper
Center Suface Hertz Stress	365,000	411,000	342,000	361,000
Max Von-Mises	228,089	265,192	220,135	231,666
Depth to VM Max	0.00825	0.00975	0.00825	0.00825
Tau-45 Max	118,865	141,247	116,011	122,824
Depth to T45 Max	0.00825	0.00975	0.00825	0.00825
Elem Length	0.0025	0.0025	0.0025	0.0025
Elem width	0.00086507	0.00087065	0.00087065	0.0008707
Element depth (uniform)	0.0015	0.0015	0.0015	0.0015
Element Volume	3.244E-09	3.264E-09	3.265E-09	3.265E-09
Depth of Uniform Section	0.015	0.015	0.015	0.015

Back Calc Roller Load for Max Htz	3381	4287	2968.5	3307.5	(Line Contact eq's.)
Cobra Mx Shear @ Roller Load	110,500	124,400	103,500	109,300	
Cobra Depth to Tau-max	0.009197	0.01036	0.008618	0.009093	
Hand Calc Semi-Width	0.011794	0.01328	0.011051	0.011665	
Theoretical Z/b	0.77980329	0.780120482	0.77983893	0.7795114	

Tau-YZ

Max Tau-YZ	93,310	101,510	84,330	87,468
Element Vol @ Tau-YZ Max	6.490E-09	6.530E-09	6.529E-09	6.530E-09
Element width @ Tau-YZ Max	0.001731	0.0017413	0.0017413	0.0017413
Depth to Tau-YZ Max	0.00525	0.00675	0.00525	0.00525

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TABLE II. STRESS DATA SUMMARY FOR 275 KSI NOMINAL STRESS

1944.5 # Load
275,000 psi nominal

Center Suface Hertz Stress	299,000	347,000	270,000	292,000
Max Von-Mises	190,800	223,000	169,804	186,484
Depth to VM Max	0.0066	0.0078	0.0066	0.0066
Tau-45 Max	101,669	119,866	90,080	99,234
Depth to T45 Max	0.0066	0.0078	0.0066	0.0066
Elem Length	0.0025	0.0025	0.0025	0.0025
Elem width	0.00684	0.00684	0.00684	0.00684
Element depth (uniform)	0.0012	0.0012	0.0012	0.0012
Element Volume	2.05E-09	2.05E-09	2.05E-09	2.05E-09
Depth of Uniform Section	.012	.012	.012	.012

Back Calc Roller Load for Max Htz	2268.5	3056	1850	2163.8
Cobra Mx Shear @ Roller Load	90,500	105,000	81,720	88,390
Cobra Depth to Tau-max	0.00753	0.00874	0.0068	0.00736
Hand Calc Semi-Width	0.009661	0.011213	0.008724	0.009435
Theoretical Z/b	0.77942242	0.779452421	0.779458964	0.780074192

Tau-YZ

Max Tau-YZ	73,313	86,135	64,731	71,023
Element Vol @ Tau-YZ Max	4.104E-09	4.120E-09	4.106E-09	4.106E-09
Element width @ Tau-YZ Max	0.001368	0.001373	0.001368	0.001368
Depth to Tau-YZ Max	0.0054	0.0066	0.0054	0.0054

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TABLE III. STRESS DATA SUMMARY FOR 200 KSI NOMINAL STRESS

1028.5 # Load
200,000 psi nominal

Center Suface Hertz Stress	228,600	281,000	197,000	224,000
Max Von-Mises	149,302	177,781	124,219	141,476
Depth to VM Max	0.0055	0.0065	0.0055	0.0055
Tau-45 Max	76,221	95,165	65,640	75,319
Depth to T45 Max	0.0055	0.0065	0.0055	0.0055
Elem Length	0.0025	0.0025	0.0025	0.0025
Elem width	0.0005561	0.0004976	0.0004976	0.0004976
Element depth (uniform)	0.001	0.001	0.001	0.001
Element Volume	1.39E-09	1.24E-09	1.24E-09	1.24E-09
Depth of Uniform Section	.010	.010	.010	.010

Back Calc Roller Load for Max Htz	1330.8	2003.8	984.9	1273.4
Cobra Mx Shear @ Roller Load	69,320	85,060	59,630	67,790
Cobra Depth to Tau-max	0.00577	0.00708	0.004964	0.005643
Hand Calc Semi-Width	0.007399	0.009079	0.006365	0.007238
Theoretical Z/b	0.779835113	0.779821566	0.779890024	0.779635258

Tau-YZ

Max Tau-YZ	55,774	69,792	48,355	55,548
Element Vol @ Tau-YZ Max	2.767E-09	2.489E-09	2.844E-09	2.844E-09
Element width @ Tau-YZ Max	0.001112	0.0009953	0.0011375	0.0011375
Depth to Tau-YZ Max	0.0035	0.0045	0.0035	0.0035

TABLE IV. STRESS-LIFE EXPONENTS - VON-MISES STRESS

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Von-Mises Stress

Zaretsky-Weibul Model:

	Flat profile	Aero-space crwn	Full crown	End Taper	Stress Life Exponent: Flat profile	Aero-space	Full crown	End Taper
200 k	0.06759	0.27580	0.17169	0.3426278	21.772754	10.95952	8.595411	12.46966
275 k	0.0016658	0.012275	0.017140	0.017385	31.213368	10.10813	8.61212	14.30812
350 k	3.2951e-6	0.0016347	0.0030762	0.0010018	0	0	0	0

Lundberg-Palmgren Model:

	Flat profile	Aero-space crwn	Full crown	End Taper	Flat profile	Aero-space	Full crown	End Taper
200 k	0.012405	0.060253	0.031450	0.083234	24.885814	10.31365	8.700604	12.38339
275 k	0.00024047	0.0038790	0.0045238	0.0047708	38.612455	10.44365	10.69005	14.71689
350 k	1.06739e-7	0.00048314	0.00053643	0.00025339	0	0	0	0

Ionnides-Harris Model: Sig infinity = 123,250 psi

	Flat profile	Aero-space crwn	Full crown	End Taper	Flat profile	Aero-space	Full crown	End Taper
200 k	0.018130	615.44	54.224	2832.	37.917057	28.7827	25.16974	38.66025
275 k	1.23014e-5	0.10478	0.14778	0.20813	52.376424	24.01495	29.44222	42.97594
350 k	3.5729e-10	0.00067109	0.00041618	3.94173e-5	0	0	0	0

Ionnides-Harris Model: Sig infinity = 87,000 psi

	Flat profile	Aero-space crwn	Full crown	End Taper	Flat profile	Aero-space	Full crown	End Taper
200 k	0.019550	8.5521	2.1267	18.7421	33.046228	19.61521	17.6695	25.69355
275 k	5.09431e-5	0.031991	0.0409537	0.050297	47.695705	17.99886	21.64958	30.59374
350 k	3.7636e-9	0.00088295	0.00054572	0.00011258	0	0	0	0

Ionnides-Harris Model: Sig infinity = 79,750 psi

	Flat profile	Aero-space crwn	Full crown	End Taper	Flat profile	Aero-space	Full crown	End Taper
200 k	0.019458	4.7623	1.31787	9.7414	32.23037	18.44873	16.58548	23.99171
275 k	6.2665e-5	0.025768	0.032541	0.039252	46.843636	17.11295	20.35292	28.63896
350 k	5.4872e-9	0.00084865	0.0005616	0.00012975	0	0	0	0

Ionnides-Harris Model: Sig infinity = 75,400 psi

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	Flat profile	Aero-space crwn	Full crown	End Taper	Flat profile	Aero-space	Full crown	End Taper
200 k	0.019351	3.4286	1.002714	6.7766	26.838714	12.88353	15.97211	23.05288
275 k	7.0031e-5	0.022682	0.028452	0.033950	34.779517	5.064689	19.61095	27.52841
350 k	6.8019e-8	0.0082598	0.00056935	0.00014005	0	0	0	0

Ionnides-Harris Model: Sig infinity = 36,250 psi

	Flat profile	Aero-space crwn	Full crown	End Taper	Flat profile	Aero-space	Full crown	End Taper
200 k	0.016814	2.9306	0.12554	0.45822	27.985639	18.07967	11.47832	16.34171
275 k	0.00015489	0.0080671	0.0097536	0.010679	42.154575	12.85879	14.1185	19.49124
350 k	3.4556e-8	0.00062068	0.00058371	0.00021886	0	0	0	0

TABLE V. STRESS-LIFE EXPONENTS - MAX. SHEAR STRESS

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Tau-45 (max Shear)

Zaretsky-Weibul Model:

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.06745	0.58225	0.158723	0.31086
275 k	0.011604	0.0095634	0.015885	0.015996
350 k	2.0346e-6	0.0013837	0.0028814	0.00084444

Stress Life Exponent

Flat profile	Aero-space	Full crown	End Taper
22.244748	12.91266	8.5673906	12.626899
43.362457	9.692382	8.55887	14.747378
0	0	0	0

Lundberg-Palmgren Model:

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.0069444	0.031346	0.019733	0.050342
275 k	0.00013057	0.0019764	0.0027945	0.0028325
350 k	4.6612e-6	0.00023506	0.00029481	0.0014178

15.524768	10.45684	8.9837669	7.6288807
16.498179	10.67511	11.276183	3.4697429
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 72,500 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.0046869	0.27053	4212.19	127035.
275 k	1.9938e-6	0.14503	0.28511	0.32107
350 k	3.7510e-11	0.00020855	0.00010173	8.1612e-6

39.842892	15.31865	37.482457	50.154207
54.553718	~~32.8122~~	39.800239	53.044987
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 50,750 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.0077406	7.7349	3.5525	52.071
275 k	1.6269	0.023712	0.038018	0.045790
350 k	8.6951e-10	0.00032879	0.00019673	4.0104e-5

34.197551	21.5117	20.946432	30.083207
107.04118	21.45017	26.391993	35.298127
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 42,050 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.0064101	1.6946	.92391	8.2463
275 k	2.8267e-6	0.012643	0.020119	0.02303
350 k	2.1900e-9	0.00032071	0.00023066	5.9725e-5

32.400679	18.32013	17.728161	25.293711
35.9129	18.42192	22.403562	29.85555
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 21,750 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.0066323	0.11468	0.093275	0.35078
275 k	7.1170e-5	0.0042272	0.0064612	0.0067356
350 k	1.2188e-8	0.00027639	0.00028743	0.00010727

28.787968	12.88263	12.357419	17.29463
43.480624	13.67476	15.605575	20.755752
0	0	0	0

TABLE VI. STRESS-LIFE EXPONENTS - ORTHOGONAL STRESS

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Tau-YZ (Orthogonal Shear)

Zaretsky-Weibul Model:

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.51489	0.511351	0.41691	0.29743
275 k	0.01649	0.026685	0.034318	0.19755
350 k	0.00017170	0.0015555	0.0042133	0.0021296

Stress Life Exponent

Flat profile	Aero-space	Full crown	End Taper
17.1095447	12.385054	9.819176	10.55566
22.886308	14.250442	10.515839	22.71232
0	0	0	0

Lundberg-Palmgren Model:

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	0.47939	0.55493	0.26025	0.288989
275 k	0.01501	0.034559	0.034535	0.024369
350 k	0.00036680	0.0039838	0.0054186	0.0040316

15.3346678	10.550025	8.2744388	9.130177
18.6090992	10.831742	9.2860402	9.020378
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 72,500 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	Infinite	Infinite.	Infinite	Infinite
275 k	4.8678e-5	1267.6	55.741	344.09
350 k	1.0132e-9	0.0017367	0.018862	0.0024942

Undfined	Due	to	Infinity
54.0469517	67.688109	40.066034	59.3355
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 50,750 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	56612.	106525.	273.59	46603.9
275 k	0.0025067	1.08995	0.57203	0.53793
350 k	2.4407e-6	0.0040379	0.011154	0.0052737

51.0066212	36.558888	21.600936	34.18178
34.7711389	28.067467	19.740881	23.18831
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 42,050 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	796.90	821.4	25.064	306.03
275 k	0.0041735	0.37645	0.25739	0.21164
350 k	1.0541e-5	0.0043050	0.0095541	0.0052092

38.7690795	25.984986	16.823724	23.46753
29.9880898	22.416262	16.51321	18.57303
0	0	0	0

Ionnides-Harris Model: Sig Infinity = 21,750 psi

	Flat profile	Aero-space crwn	Full crown	End Taper
200 k	6.7985	5.595	1.3429	2.5082
275 k	0.0074825	0.085401	0.07714	0.21116
350 k	9.4839e-5	0.0043114	0.0070480	0.0046565

23.8928573	15.319522	11.219444	13.44035
21.9005201	14.971364	11.997156	19.12399
0	0	0	0

TABLE VII. LAMINA WIDTH EFFECT VS. FATIGUE LIFE ERROR (0.5"d x 0.5"l + AEROSPACE CROWN)

Number of Lamina	Lamina Width Inch	%	L10 Life per LP Theory hours	% Diff.
4	0.125	25	7131	-21.9
5	0.10	20	8436	- 7.7
10	0.05	10	9261	+ 1.4
15	0.033	6.7	9174	+ 0.4
20	0.025	5.0	9136	0.0

TABLE VIII. LAMINATED ROLLER MODEL LIFE COMPARISON (0.5"d x 0.5"l + AEROSPACE CROWN)

Nominal Max. Hertz Stress	**Roller Load** (#)	**BRG Pgm. Stress** (psi)	**Life** (hrs)	**SHABERTH Stress** (psi)	**Life** (hrs)
200 ksi	1028.5	225,496	9263	224,809	9136
275 ksi	1944.5	296,910	965	296,408	924
350 ksi	3149.0	369,852	158	369,403	142

TABLE IX. FULLY CROWNED LAMINATED ROLLER COMPARISON

Nominal Max. Hertz Stress (ksi)	Max. Hertz Stress (psi) 20 Lamina	40 Lamina	Ellip.Thy	% Difference Stress	Life
200	263,180	263,240	272,600	3.5%	37%
275	328,888	328,940	337,000	2.5%	24.5
300	397,760	--	395,700	OVERSPILL	